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Repeatability of Energy Consumption Test Results For Compact Refrigerators

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David A. Yashar

Abstract

Recently, the United States Department of Energy (DOE) has been interested in examining the current procedure that is used to measure the energy consumption of compact refrigerators (ANSI/AHAM HRF-1). As part of the DOE's Appliance Standards Program, NIST performed round-robin tests of three compact refrigerators using their facilities in Gaithersburg, MD and three independent laboratories.

The round-robin test results revealed several major issues, which caused significant differences in the measured energy consumption from laboratory to laboratory. After the completion of the round robin tests, the compact refrigerators used in this study underwent extensive testing at NIST to further examine the effects of the noted problems with the procedure.

This paper reports the results of the round robin tests, and the results of the extensive testing at NIST. This paper also suggests possible changes to the testing procedure that would reduce problems with the repeatability of the test results.

Keywords: Refrigerator, Energy Consumption, Efficiency, Test Procedure, AHAM HRF-1

1: Introduction

Currently, in the United States, the Federal Register designates the maximum allowable energy that can be used by a refrigerator. The government puts this limitation on the manufacturers, but does not require that the products be checked outside of the manufacturer's facilities. Instead, the government relies on competitors in the free market to test products and report any non-compliance. If a model is reported as being non-compliant, DOE notifies the manufacturer of the unit that they must send their data from the energy consumption test to DOE. Unfortunately, it has often been the case with compact refrigerators that the data from tests performed at the manufacturer's laboratories does not agree with the data obtained elsewhere. To avoid such problems, manufacturers often contract independent laboratories to perform these tests, and compare the results with their own data before bringing the product to the market.

The Association of Home Appliance Manufacturers (AHAM) publishes the procedure for refrigeration energy consumption measurement. The AHAM HRF-1 test procedure booklet outlines the steps for measuring the volume of a refrigerator cabinet and for measuring the energy consumption of a refrigerator, as well as various other tests. DOE utilizes the basic procedures outlined in AHAM HRF-1 as the platform upon which refrigerators are to be tested for energy consumption. DOE was prompted to examine the test procedure for clarity and repeatability as a result of many compact refrigerators returning large variances in the test results from the same test procedure performed at different laboratories.

The AHAM HRF-1 tests compact refrigerators (generally used in dormitory rooms, hotel rooms, and lounges) in the same way full sized household refrigerators are tested. Compact refrigerators, unlike full sized refrigerators, usually do not use forced air circulation. The evaporator for these models is a flat rolled and pressure blown metal sheet which acts as the floor (and sometimes the sides and ceiling) of the freezer compartment. Items in the freezer are cooled by conduction as they are placed in direct contact with the evaporator, while the fresh food compartment is cooled by natural convection generated by the freezer compartment above it.

2: AHAM Procedure

The ANSI/AHAM HRF-1 booklet outlines the testing procedure that is used to measure the volume of the refrigerated compartment and to evaluate the energy consumption of refrigerators. It is important to examine the procedure described for the measurement of the refrigerated volume, because it is this parameter which dictates the limit on the amount of energy that a refrigerator may consume.

The procedure for the measurement of the volume of a refrigerator is essentially a list of spaces and features that should (baskets, chiller trays, etc.) and shouldn't (air ducts, drip troughs, etc.) be included in the refrigerated volume. Although the procedure is rather straight forward, it can be quite tedious. A refrigerator compartment is separated into smaller volumes, which are measured and summed to give the total volume. For compact refrigerators in particular, fairly unrepeatable results are generally found. This is due to the fact that the dimensions that are measured may not be large compared to the uncertainty of the measurements. Although tolerances are specified, it can often be quite difficult to measure the small features inside a compact refrigerator within these tolerances.

The energy consumption test procedure begins with the placement and instrumentation of the refrigerator. The refrigerator is placed in a test chamber on top of a non-thermally conductive platform. The ambient air in the chamber is 32.2 °C ± 0.6 °C (90 °F ± 1 °F), with minimal temperature gradients and air circulation. The humidity of the air is not specified. The temperatures inside the refrigerator compartment are measured with either thermocouples or electric resistance thermometers. Thermocouples, which are the preferred measurement device due to the cost, are to be accurate to within 0.6 °C (1.0 °F). The thermocouples used to measure the temperature inside the refrigerator are each embedded inside a metallic cylinder. The purpose of this cylinder is to add thermal mass to the temperature sensor to minimize fluctuations in the measurement.

The reported temperatures of the compartments of the refrigerator are the average of the temperatures measured in these compartments through the duration of the test period. The test period is three hours long plus the remainder of the next cycle of the compressor. A watt-hour meter is used to measure the electrical energy input to the refrigerator during the test period. The time duration of the test is used to compute the energy used by the refrigerator on a per year basis. This test is performed two times with the thermostat at different settings (once at the median setting and once at either the warmest or coldest setting), so that a standard reference temperature will be bounded by the results of the tests. Linear interpolation of the results of the two tests gives the energy consumption at the reference temperature.

If the freezer compartment volume is greater than 14.2 L (0.5 ft^3), then it is designated as a "basic refrigerator" by the standard. The freezer compartment of a basic refrigerator is filled to 75 % full capacity with packages of frozen food or alternatively, packages of hardwood sawdust soaked in water. Several of the packages (generally, three for compact refrigerators) have a thermocouple placed in the center, and are used to measure the temperature of items that would be placed in the freezer compartment. The reference temperature for this type of refrigerator is –9.4 °C (15 °F) in the freezer compartment.

If the freezer compartment is less than 14.2 L (0.5 ft^3), it is designated as an "all-refrigerator" by the standard. For all-refrigerators, only the refrigerator compartment temperatures are needed and the freezer compartment is to be empty. The reference temperature for this type of refrigerator is 3.3 °C (38 °F) in the refrigerator compartment.

3: Procedure of This Study

In order to examine the repeatability of the results obtained from the energy consumption tests, a round robin test plan was implemented. Three compact refrigerators were acquired by NIST in Gaithersburg, MD. These units were chosen based on similar units returning non-repeatable energy consumption test data. These units were sent to three independent laboratories, where they underwent testing to measure the energy consumption and internal volume as per AHAM HRF-1. After each unit was tested at all three laboratories, they were returned to NIST where they were tested again.

It was found that the results from the independent laboratories did not agree, with a few factors being attributed to the differences. One of the factors contributing to the differences was trauma to each unit as a result of the shipping process causing a slight degradation of the performance each time. Since these units are an integral system of many components, the performance of the system is dependent on how well these components work together. The roughness of the handling of the refrigerator during the shipping process degrades the cooperation of the components of the system. Door seals are another important factor to the performance of the system. The shipping process can also affect this if the magnet that holds the door tightly against the cabinet sustains a slight deformation, which can result from the unit being bumped. If the tight seal of the door to the cabinet were lost, the performance of the entire system would be degraded.

The round robin test plan was, however, very useful in that it showed that there was some misinterpretation of the procedure. Two of the three independent laboratories that were used in this study had made a few errors in the execution of the tests as a result of such misinterpretations. Particularly, in the case of the laboratory referred to as Lab 3 in this study, some of the errors that were made during the tests were severe enough to warrant a retest. The data from this laboratory that is cited in this report is a product of the retest. The fact that errors were made, however, indicates that certain areas of the booklet should be written more clearly so that understanding of the steps of the procedure could be achieved more readily. The round robin tests were also very beneficial in that other matters of importance were brought to attention through discussions with the engineers that performed the tests.

4: Results and Discussion

The following sections will discuss the results from the round robin tests. The results from further testing at NIST that were performed as a result of discussions with other engineers performing these tests, are also presented in this section. The three units selected will be described in detail during the discussion of each unit's results from the energy consumption tests.

4.1: Volume Measurement

Volume measurement results from NIST as well as the three independent laboratories are shown normalized to the manufacturer's reported volume on the energy guide label in Figure 1. The three units, shown left to right in the figure, were labeled as having volumes of 51.0 L (1.8 ft^3) for unit A, 121.8 L (4.3 ft^3) for unit B, and 172.7 L (6.1 ft^3) for unit C. The results from NIST and two of the three independent laboratories consistently agreed with the manufacturer's value to within 10 %. The second laboratory, however, measured the volume to be considerably smaller for all three refrigerators. The results from this laboratory deviated from the manufacturer's value by as much as 40 % for the smallest unit.

Upon examination of the calculations included with the results from the second laboratory, it was noticed that a space, which should have been included in the volume calculation, was overlooked. Specifically, the useable space in the doorway of each refrigerator was not added to the volume of the refrigerators.

Barring the data from the second laboratory, the volume measurement data could be more unified if a different procedure was employed. The measurement of the volume is a rather tedious task, resulting in more opportunity for error. If the compartment volume was measured by a less tedious procedure, better agreement could be obtained.

As an alternative method of measurement that should return more repeatable results, the following is suggested. The compartment of interest would be filled with water (or another fluid of known density) contained within a plastic or rubber bladder. This bladder could then be removed with the water and weighed; or the whole system could be weighed before and after. The mass of the water could then be used to determine the volume within the cabinet. This method of volume measurement will be performed in the near future to determine repeatability.

4.2: Energy Measurement

4.2.1: Results for Unit A

A sketch of unit A is shown in Figure 2. The energy guide labeled this unit as a 51.0 L (1.8 ft^3) refrigerator. It has a small compartment located in the upper right side, which serves as a freezer compartment. This freezer compartment is less than 14.2 L (0.5 ft^3), which makes this unit fall into the category termed "all-refrigerator" by the AHAM test procedure.

The evaporator of this unit is made from flat sheets of metal with a path for refrigerant flow between them. The evaporator serves as the floor of the freezer compartment as well as the left and right sides of the compartment. There is no source of forced air circulation in this unit; therefore when liquid refrigerant is boiled in the evaporator, it cools the refrigerator mainly by natural convection.

The condenser of this unit can be seen on the rear view of Figure 2. It is a serpentine tube, oriented vertically along the back of the cabinet. Thin metal wires serve as fins for this heat exchanger. Again, there is no source of forced air circulation for this unit; therefore it expels heat during operation mainly by natural convection.

Figure 2 also shows the locations of the temperature measurements needed to perform the energy consumption test. The locations labeled as T1, T2, and T3 are shown as cylinders. The procedure calls for the thermocouples to be embedded inside of brass or copper cylinders, which are used to add thermal mass to the temperature sensors during the measurements. Since this unit is an "all-refrigerator", no temperature measurements were needed in the freezer compartment.

The AHAM test procedure calls for two tests to determine the energy consumption. For the first test, the thermostat was set to the median setting. The temperature of the refrigerator was measured by averaging the temperatures reported by the thermocouples over the duration of the test period of 3 h plus the remainder of the last compressor cycle. This value was compared to the reference temperature of 3.3 °C (38.0 °F) to determine if the second test should be set at the warmest or coldest setting. A linear equation was then generated from the data, which relates the energy consumption to the measured refrigerator temperature. This equation was used to determine the energy consumption at the reference temperature. The results from the three independent laboratories are shown below in Table 1.

Laboratory	Energy Consumption	Difference from Energy Guide
Lab 1	$321 \frac{kW \bullet h}{year}$	+ 25.4 %
Lab 2	$328 \frac{kW \bullet h}{year}$	+ 28.1 %
Lab 3	$378 \frac{kW \bullet h}{year}$	+ 47.7 %

Table 1 Measured Energy Consumption from Independent Labs (Unit A)

It is noted that Lab 1 made two errors in the execution of the procedure while testing this unit. The first error was that only two thermocouples were placed in the refrigerator compartment, instead of three. The thermocouple that was missing corresponds to T1 in Figure 2. Due to the fact that this thermocouple should be placed at the highest location, and that there was no source of air circulation within the cabinet, this location would represent a temperature that was slightly warmer than the other two thermocouple locations. This was in fact the case; it was noticed that this location was usually on the order of 1.5 °C warmer than that of T2, which was incidentally warmer than T3. Had this thermocouple been in place, the average compartment temperature would have been reported as being slightly warmer. This would have ultimately resulted in the reported energy consumption being slightly higher.

The second error made by this laboratory was the freezer compartment of this unit being loaded with three frozen spinach packages. The freezer compartment of this unit should have been empty. The effect of this error, however, does not make much of a difference in the final value of the energy consumption as will be discussed in the later section of this report dealing with unit B.

After these units were returned to NIST, energy consumption measurements were performed three times with slight variations in the procedure to examine the effects of these variations. For the first test at NIST, the unit was placed with its back as close to the wall as allowed by mechanical deterrents, approximately 3.8 cm (1.5 in). For the second test, the rear of the unit was placed 25.4 cm (10 in) from the wall behind it. The instructions as to the placement of the unit with respect to the wall state that it should be placed "in accordance with the manufacturer's instructions or as determined by mechanical stops on the back of the cabinet." (AHAM HRF-1 section 7.4.2)

It was hypothesized that this unit would consume less energy if it were placed farther from the wall, since the condenser was mounted on the rear of the unit and relied on free convection to expel heat. By moving the unit away from the wall, air would flow over the condenser more easily resulting in better heat transfer, which would allow heat to be removed from the system faster, resulting in less compressor run time. This was exactly the case as determined from these tests. The test data is shown below in Table 2, and sample uncertainty calculations for data taken at NIST can be seen in the appendix. The results of these tests showed that the energy consumption decreased by almost 12 % when sufficient space for airflow was provided to the condenser.

Distance from rear wall	Energy Consumption	Difference from Energy Guide
3.8 cm (1.5 in.)	$(331.44 \pm 3.70)\ \frac{kW \bullet h}{year}$	+ 29.5 %
25.4 cm (10 in.)	$(296.37 \pm 3.27)\ \frac{kW \bullet h}{year}$	+ 15.8 %

Table 2 Measured Energy Consumption varying Distance to Rear Wall (Unit A)

The third test performed on this unit examined the sensitivity of the performance of this unit to the ambient temperature. This test was performed with the ambient temperature being 33.3 °C (92.0 °F) instead of the specified 32.2 °C (90.0 °F). This temperature was chosen because the test procedure declares an accuracy of 1 °F for the measurement device and a 1 °F tolerance for the ambient temperature. For this test, the rear of the unit was placed as close to the wall as possible, as was the case for the first test. The result of this test is shown below with the result from the first test for comparison.

Ambient Temperature	Energy Consumption	Difference from Energy Guide
32.2 °C (90.0 °F)	$(331.44 \pm 3.70)\ \frac{kW \bullet h}{year}$	+ 29.8 %
33.3 °C (92.0 °F)	$(443.68 \pm 5.75)\ \frac{kW \bullet h}{year}$	+ 73.3 %

Table 3 Measured Energy Consumption varying Ambient Temperature (Unit A)

The results show that when the ambient temperature is 1.1 °C (2.0 °F) warmer than the specified temperature, the energy consumption was measured to be nearly 34 % higher.

Theoretically, a higher ambient temperature would result in a higher condensing temperature, slower mass flow rate of refrigerant, and overall lower coefficient of performance. It was seen during these tests that the compressor power did not change between the tests at different ambient temperatures. It was noticed that, when tested at the higher ambient temperatures, the compressor ON time was a much larger portion of the whole compressor cycle than it was during the tests at the specified ambient temperature. The end result was that the compressor had to operate for a greater amount of time to expel heat to the ambient, which resulted in a much greater value for the energy consumption.

4.2.2: Results for Unit B

A sketch of unit B is shown in Figure 3. The energy guide labeled this unit as a 121.8 L (4.3 ft^3) refrigerator. The compartment located at the top of the cabinet serves as a freezer. This freezer compartment is approximately 14.2 L (0.5 ft^3). During the round robin tests, the data for the measurement of this compartment ranged from 13.3 L (0.47 ft^3) to 15.9 L (0.56 ft^3). This caused a problem because the freezer compartment volume of 14.2 L (0.5 ft^3) is the limit defining the classification of the unit. Units with a freezer compartment volume less than 14.2 liters (0.5 ft^3) are classified as “all-refrigerator” and tested in the same way as unit A of this study; while units with a freezer compartment larger than this limit are classified as a “basic refrigerator” and require a slightly different test procedure.

The freezer compartment of this unit is similar to that of unit A, with the exception that it spans the entire width of the cabinet. There is no source of forced air circulation in this unit; therefore, when the refrigerant is boiled in the evaporator, it cools the refrigerator mainly by natural convection. Conduction heat transfer is used to cool items in the freezer compartment.

This unit’s condenser is built into the left and right outer walls, and is not visible to the user. The condenser heats up the outer walls of the cabinet and heat is removed from the walls by natural convection, as there is no source of forced air over the walls.

The locations of the three thermocouples required for the refrigerator compartment are also shown in Figure 3. These are the only locations needed if the unit was tested as an all-refrigerator, and the freezer compartment is to be empty. If the unit were tested as a basic refrigerator, then three additional thermocouples would be required in the freezer compartment, which would contain load packages.

Thermocouples that are used to measure the temperature in the freezer compartment are not placed inside the brass or copper cylinders that are used for the refrigerator compartment temperatures. Instead, each thermocouple is placed inside a load package. The load packages are used to create a thermal load on the freezer compartment. The procedure gives two options for load package material. The first option is plastic bags filled with a mixture of sawdust and water (mixed to a specified density). The other option is packages of frozen vegetables; chopped spinach is suggested by the procedure. The ISO standard procedures (ISO 7371, ISO 8187, ISO 5155, and ISO 8561) for the measurement of energy consumption dictates that packages containing a specific recipe, wrapped similarly to the sawdust packages, is the only type of package that may be used. The load packages must fill up 75 % of the volume of the freezer compartment and are to be stacked in a pyramidal shape. The three load packages containing thermocouples are to be positioned in the freezer compartment in locations that represent the bottom-back, center, and front-top of the compartment.

The freezer compartment temperature is the average of all three freezer thermocouples over the test period. Similarly, the refrigerator temperature is the average of the temperatures

measured in the refrigerator compartment. The energy consumption is determined in the same way as for an all-refrigerator with the exception that the standard reference temperature for a basic refrigerator is –9.4 °C (15.0 °F) in the freezer compartment, provided the refrigerator compartment is colder than 7.2 °C (45.0 °F). The values of the measured energy consumption from the independent laboratories are shown below in Table 4.

Laboratory	Energy Consumption	Difference from Energy Guide
Lab 1	$349 \frac{kW \bullet h}{year}$	+ 1.75 %
Lab 2	$416 \frac{kW \bullet h}{year}$	+ 21.3 %
Lab 3	$450 \frac{kW \bullet h}{year}$	+ 31.2 %

Table 4 Measured Energy Consumption from Independent Labs (Unit B)

A few things need to be noted about the data shown above. First of all, it was suspected that this unit was damaged somewhere during the shipping between the first and second laboratory. It was noted upon its arrival at the second laboratory that the door was slightly dented. Secondly, this unit was not tested using the same procedure at each laboratory. Lab 1 tested this unit as a basic refrigerator, using the freezer temperature to determine the energy consumption; however, they only used one thermocouple in the freezer compartment. Lab 2 measured the freezer compartment to be 13.3 L (0.47 ft^3), and therefore tested it as an all-refrigerator. Lab 3 tested this unit as a basic refrigerator. The first and third laboratory (which tested this unit as a basic refrigerator) used packages of frozen chopped spinach to load the freezer compartment.

After this unit was returned to NIST, four separate tests were performed. The first two tests at NIST were performed as if the unit was a basic refrigerator. One using packages of frozen spinach to load the freezer compartment, and one using the water soaked sawdust packages described above.

To reiterate the temperature measurement technique for the freezer compartment, three packages that contained a thermocouple in the center are placed among the other packages in the freezer compartment. These packages are positioned in such a way that the temperatures represent those of the bottom-back, center, and front-top of the freezer compartment. Since conduction heat transfer is used to remove heat from the temperature sensing packages and the air temperature of the freezer compartment was found to be similar to that of the refrigerator compartment, the observed temperatures are a strong function of the location of the sensing packages. The temperature differences that are observed between the sensing packages are mainly due to contact resistance to conduction heat transfer between the packages. For this reason, a package placed on the bottom layer will be considerably colder than packages that are farther from the evaporator.

The main difference between the two types of packages is how they are wrapped. The packages of frozen spinach are packaged in a thin cardboard box, and the box is wrapped in waxed paper. The water soaked sawdust packages are sealed in a thin layer of plastic (i.e. a sandwich bag). Another difference that occurs when spinach packages are used is due to voids

that may exist inside the packages. The argument for testing both types of packages is that the water soaked sawdust packages would offer less resistance to heat transfer in this situation. As a corollary, the amount of resistance to heat transfer offered by spinach packages is not only unknown, but would vary from package to package or even from brand name to brand name of spinach. This variability could be controlled more easily with the water soaked sawdust packages. The results from these two tests are shown below in Table 5.

Package Type	Energy Consumption	Difference from Energy Guide
Spinach	$(420.66 \pm 3.72)\ \frac{kW \bullet h}{year}$	+ 22.6 %
Water Soaked Sawdust	$(373.57 \pm 3.17)\ \frac{kW \bullet h}{year}$	+ 8.9 %

Table 5 Measured Energy Consumption varying Load Package Type (Unit B)

The results of these tests showed that the freezer compartment temperature was measured to be much colder with the sawdust packages, which resulted in a value for the energy consumption being nearly 13 % lower than the test with the spinach packages.

NIST performed a third test on this unit as an all refrigerator. This was done because the range of volume measurement data for the freezer compartment fell both above and below 14.2 L (0.5 ft^3), which is the defining parameter for the unit's classification. For this test, only the refrigerator compartment temperatures were measured, and the freezer compartment was empty. The results of this test (Table 6) agreed very well with the results of the second laboratory, which also tested this unit as an all-refrigerator.

Unit B tested as all-refrigerator	Energy Consumption
NIST	$(414.51 \pm 5.51)\ \frac{kW \bullet h}{year}$
Lab 2	$416\ \frac{kW \bullet h}{year}$

Table 6 Measured Energy Consumption varying Model Classification (Unit B)

It is interesting to note that the value of the energy consumption for this refrigerator is between the two values measured when this unit was tested as a basic refrigerator (although closer to the spinach package test). The difference was the compressor on/off cycle being much faster when the freezer compartment was empty. A typical cycle for this unit with the freezer loaded with spinach packages was 50 min ON and 65 min OFF, and when tested with an empty freezer it was 17 min ON and 20 min OFF. The difference in cycle times is caused by the thermal mass added by the items inside the freezer compartment. The added thermal inertia increases the time to cool down when the compressor is running, and it keeps the refrigerator cool when the compressor is not running.

The last test that was performed on this unit was done at a slightly higher ambient temperature, as was done with model A. Again, it was tested with the ambient temperature being 33.3 °C (92.0 °F) instead of the prescribed 32.2 °C (90.0 °F). It is noted that this test was

performed using the procedure for a basic refrigerator, with spinach packages in the freezer compartment. The results from this test are shown below with the results of the first test as a basis of comparison (Table 7).

Ambient Temperature	Energy Consumption	Difference from Energy Guide
32.2 °C (90.0 °F)	$(420.66 \pm 3.71)\ \frac{kW \bullet h}{year}$	+ 22.6 %
33.3 °C (92.0 °F)	$(558.58 \pm 6.60)\ \frac{kW \bullet h}{year}$	+ 62.9 %

Table 7 Measured Energy Consumption varying Ambient Temperature (Unit B)

The results show that the energy consumption of this unit increased by nearly 33 % in response to a 1.1 °C (2.0 °F) increase in temperature. This is similar to the results of the same tests on unit A.

4.2.3: Results for Unit C

A sketch of unit C is shown in Figure 4. The energy guide labeled this unit as a 172.7 L (6.1 ft^3) refrigerator. It has a freezer compartment located at the top of the cabinet. This freezer compartment is indisputably greater than 14.2 L (0.5 ft^3), and is therefore designated as a "basic refrigerator" by the AHAM test procedure.

The evaporator for this unit is structurally similar to that of units A and B, however its size and shape are different. The evaporator for this unit makes up the floor of the freezer compartment, is bent upwards at the rear of the compartment, then extends forward to make up the ceiling of the freezer compartment. This evaporator geometry is much more efficient in isolating the freezer compartment from the refrigerator compartment than the other two units. Consequently, the air temperature inside this compartment was much colder than the air temperature in the refrigerator compartment; as opposed to the air temperature in the freezer compartment being the same as in the refrigerator compartment as was the case with unit B.

The condenser for this unit is mounted below the cabinet. It uses a small fan to generate airflow from the rear to the front, underneath the cabinet; i.e. the condenser uses forced air convection to remove heat from the system.

The energy consumption test for this unit requires that six temperatures be recorded for the duration of the test period, three in the refrigerator compartment and three in the freezer compartment. The locations of the refrigerator compartment temperature sensing weighted thermocouples are also shown in the sketch. For the sake of clarity, the freezer compartment temperature sensors are not shown. The freezer compartment temperatures are taken inside the freezer packages, as was explained in the discussion for unit B. The freezer compartment temperatures are used to determine the energy consumption at the reference temperature of –9.4 °C (15.0 °F).

The data from the energy consumption tests at the first two independent laboratories is shown in Table 8; however, some explanation is needed (below). The data from the third laboratory is left out of this section because errors in the execution of the energy consumption test of this unit lead to erroneous results. It is of importance to note that all of the tests

performed on this unit at the independent laboratories were done with packages of frozen spinach in the freezer compartment.

Laboratory	Energy Consumption	Difference from Energy Guide
Lab 1	$557 \dfrac{kW \bullet h}{year}$	+ 53.0 %
Lab 2	$362 \dfrac{kW \bullet h}{year}$	- 0.55 %
Lab 3	N/A	N/A

Table 8 Measured Energy Consumption from Independent Labs (Unit C)

The unit that was tested at the first laboratory was destroyed during the shipping process, en route to the second laboratory. It is not known whether or not this unit was damaged before it was tested at the first laboratory; however, the engineers at this laboratory did not know of any visible damage to the unit when it was tested. After the damage was noted at the second laboratory, this unit was replaced with another unit of the same manufacturer and model, and the round robin test plan was resumed.

After this unit was received at NIST, three separate energy consumption tests were performed. The first test was performed with packages of frozen chopped spinach in the freezer compartment and housing the thermocouples. The second test was performed with packages of water soaked sawdust in the freezer compartment. The third test was performed with spinach packages in the freezer compartment, but with the ambient temperature outside the cabinet being 33.3 °C (92.0 °F) instead of the 32.2 °C (90.0 °F) temperature specified by the procedure. The results from the tests at NIST are summarized in Table 9 below.

Ambient Temperature	Type of Load Package	Energy Consumption	Difference from Energy Guide
32.2 °C (90.0 °F)	Spinach	$(400.14 \pm 3.50) \dfrac{kW \bullet h}{year}$	+ 9.9 %
32.2 °C (90.0 °F)	Water Soaked Sawdust	$(382.45 \pm 3.14) \dfrac{kW \bullet h}{year}$	+ 5.1 %
33.3 °C (92.0 °F)	Spinach	$(430.11 \pm 4.75) \dfrac{kW \bullet h}{year}$	+ 18.2 %

Table 9 Measured Energy Consumption from NIST (Unit C)

These results show that the type of package was not as influential as was the case with unit B. This unit consumed 4.6 % more energy with the spinach packages than with the sawdust packages (as opposed to the 13 % penalty seen by unit B.) The reason for this has to do with the geometry of the evaporator. The main mode of heat removal from items in the freezer compartment is conduction heat transfer. However, due to the different geometries of the evaporators, the air temperature of the freezer compartment of unit C is much colder than the air temperature in unit B. This provides a much colder source for heat addition into the temperature

sensing packages. This resulted in a much smaller temperature gradient in the packages, and overall colder packages.

By comparison of the first and third tests performed at NIST, it is seen that unit C consumed 7.5 % more energy at the elevated ambient temperature of 33.3 °C (92.0 °F) than at the prescribed ambient temperature. Again, this is not nearly as severe as the 33 % and 34 % penalties seen by units A and B. The reason for this is that the condenser for this unit uses forced air convection, as opposed to free convection used by units A and B. The elevated ambient temperature does make it more difficult to transfer heat from the condenser to the ambient, however not as much as for a unit which relies on free convection.

5: Summary and Conclusions

Three compact refrigerators were used in a round robin test plan to examine the repeatability of energy consumption test results obtained following AHAM HRF-1. The compact refrigerators were tested at three independent laboratories, then underwent extensive testing at NIST to determine the causes of non-repeatability of the test results. As a result of these tests, the following observations are made regarding the possible causes of non-repeatability:

1. The measurement of the internal volume of compact refrigerators involves rather tedious measurements within a small cabinet, which results in great opportunity for error. It is recommended that alternative methods be examined for better repeatability of results.
2. Some of the steps involved in the execution of the energy consumption test procedure were misinterpreted by two of the laboratories involved in the round robin tests. It is recommended that the procedure be rewritten in a step-by-step format. For example, isolating procedures for different types of refrigerators, in lieu of integrating the procedural steps to save space.
3. Units that have a condenser mounted on the rear of the cabinet and rely on free convection to remove heat from the system are sensitive to their distance from the wall. The results of the tests show that a unit of this type consumes less energy when it is placed far from the wall. Currently, it is the responsibility of the manufacturer to specify how far from the wall the unit should be during operation. This leaves a loophole for the energy consumption test open for the manufacturer. The manufacturer has the ability to specify a distance that may be unrealistically large for it's actual placement in everyday use and this is the distance that would be used for the test. Also, the current procedure is not a good basis of comparison of two different units if the manufacturers of these units do not specify the same distance from the wall. The test procedure should specify this distance rather than leaving it to the discretion of the manufacturer.
4. Units that have a free convection condenser are very sensitive to the ambient temperature. The two units in this study that employ such a condenser consumed much more energy at an ambient temperature 1.1 °C (2 °F) higher than the specified ambient temperature (which is a possible occurrence taking into account a 0.6 °C (1 °F) tolerance on the ambient temperature and a 0.6 °C (1 °F) measurement uncertainty). Conversely, the unit that used a different type of condenser was not affected to the same extent.
5. The results of the energy consumption tests will vary with the types of packages used to load the freezer compartments. The test procedure is geared towards full sized household units, which use forced convection heat transfer to remove heat from items in the freezer compartment. Since compact units generally remove thermal energy from items in the freezer compartment by conduction, the temperature of items in the freezer compartment will have a strong dependence on the location of the temperature sensors. The contact resistance from the wrapping of the packages amplifies the temperature gradients seen in these types of refrigerators. It is recommended that only the water soaked sawdust packages (or alternatively, a package similar to the ISO standard) be used when testing this type of unit.

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Appendix A: Figures

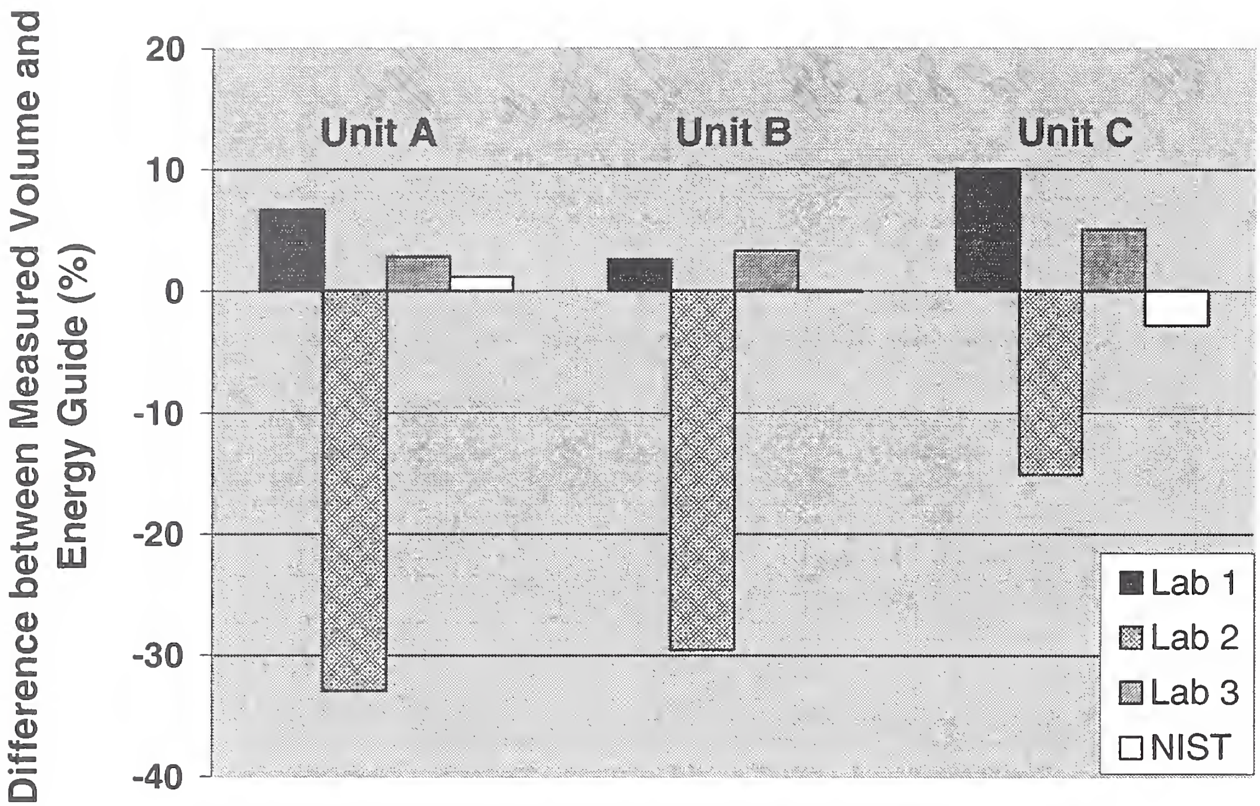

Figure 1. Volume Measurements Taken by Three Independent Laboratories and NIST

$$\left(\frac{V_{lab} - V_{energy\_guide}}{V_{energy\_guide}}\right) \times 100$$

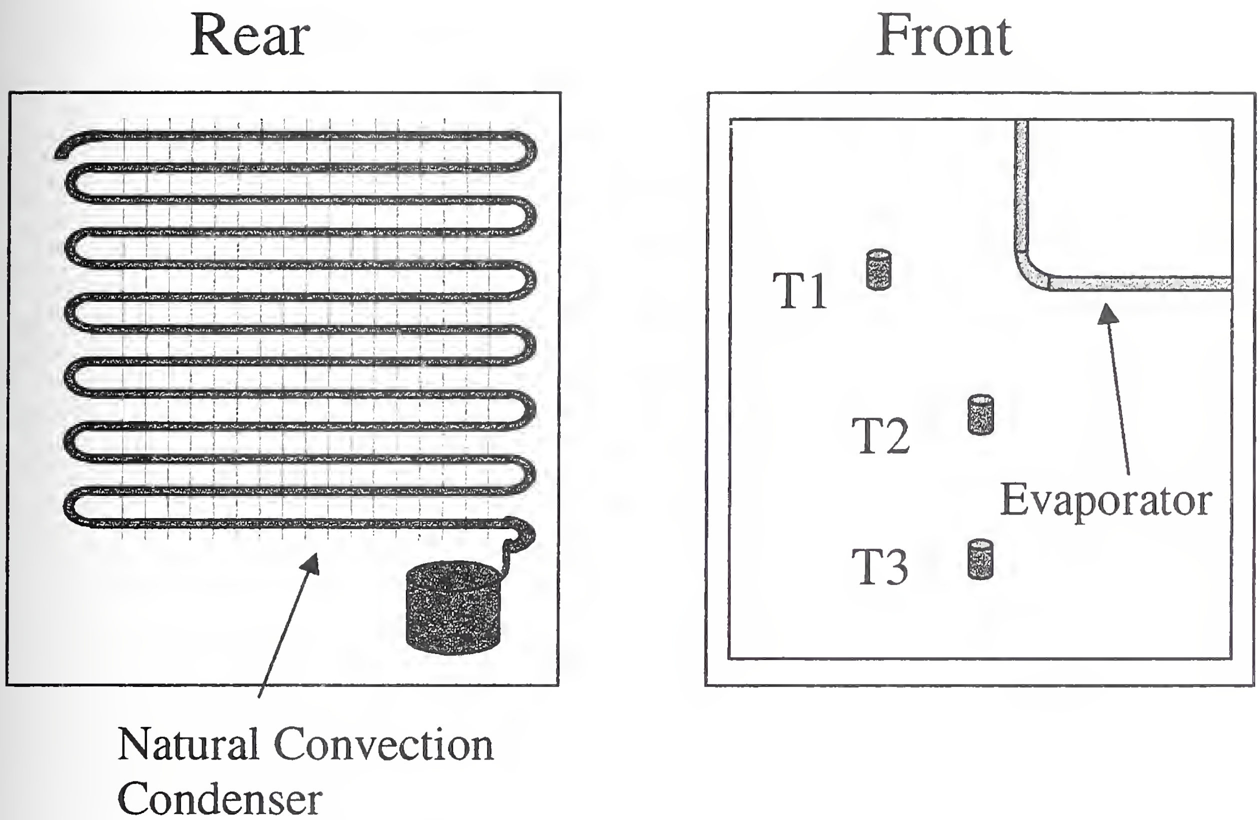

Figure 2. Sketch of 51.0 L (1.8 ft^3) Compact Refrigerator (Unit A)

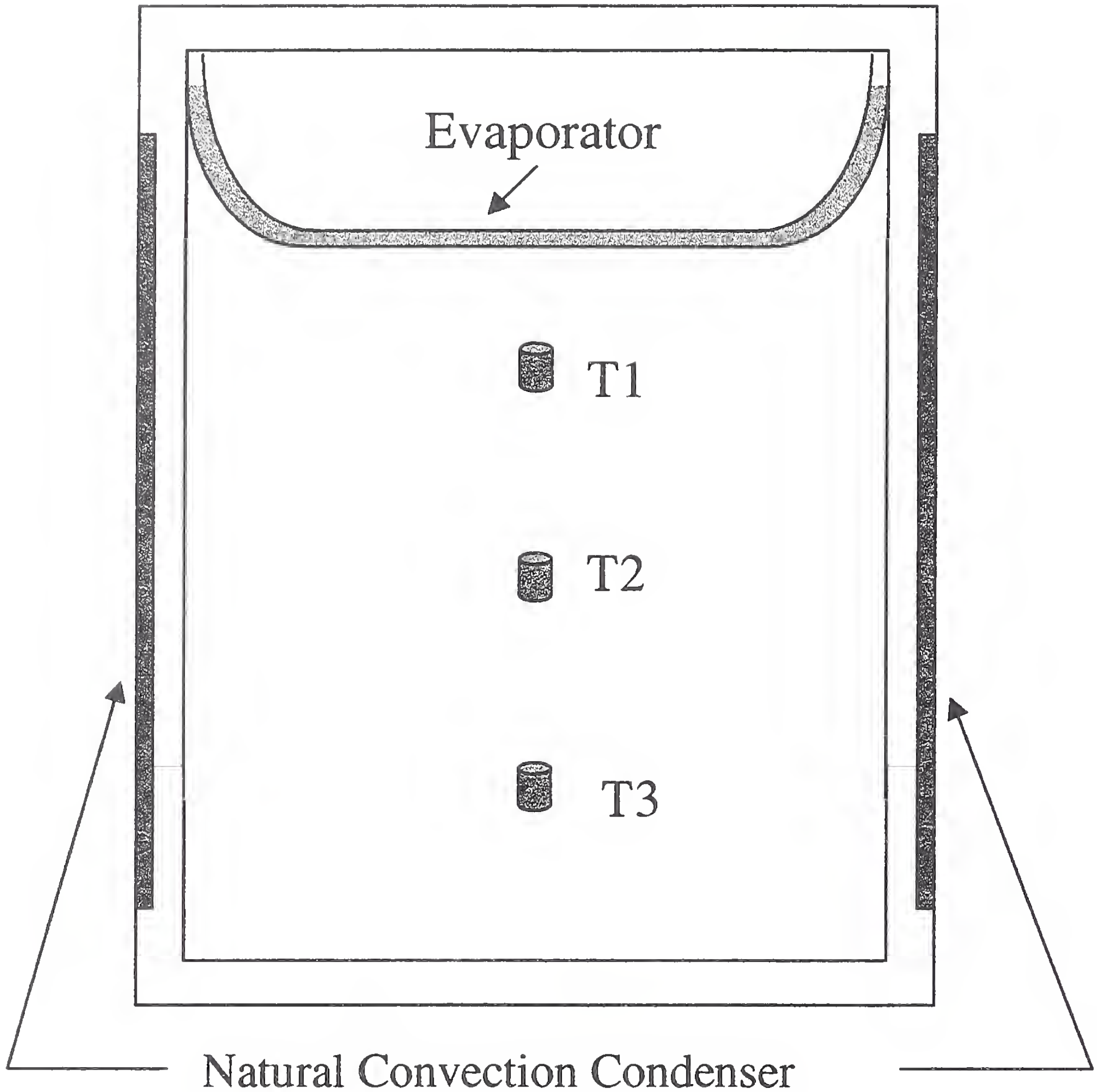

Figure 3. Sketch of 121.8 L (4.3 ft^3) Compact Refrigerator (Unit B)

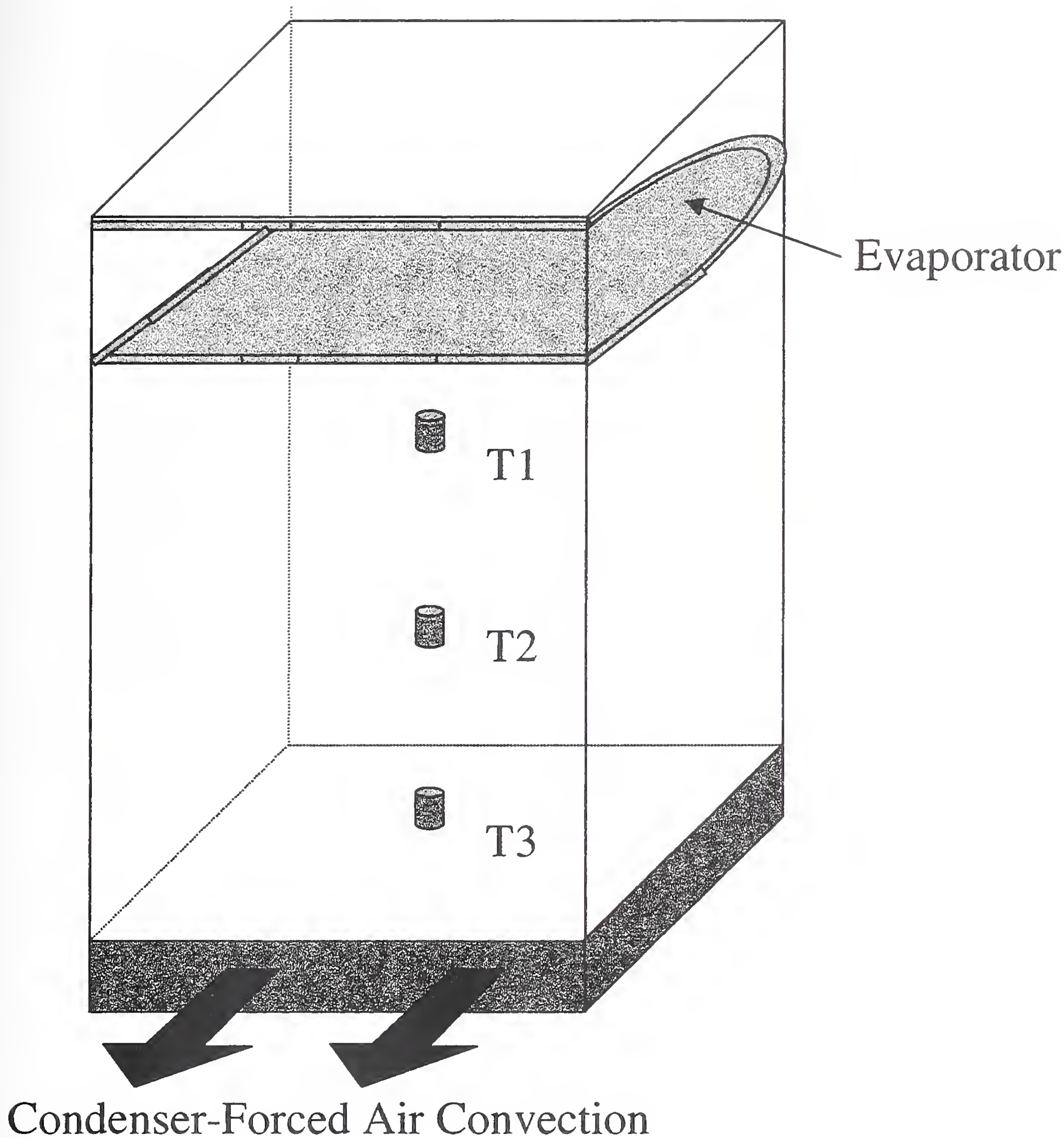

Figure 4. Sketch of 172.7 L (6.1 ft^3) Compact Refrigerator (Unit C)

Appendix B: Equations Used for Analysis

Equation for energy consumption at reference temperature

$$E = \frac{E_1(T_{ref} - T_2) - E_2(T_{ref} - T_1)}{T_1 - T_2}$$

Uncertainty Analysis

$$\frac{\partial E}{\partial T_1} = \frac{(E_1 - E_2)(T_{ref} - T_2)}{(T_1 - T_2)^2}$$

$$\frac{\partial E}{\partial T_2} = \frac{(E_1 - E_2)(T_{ref} - T_1)}{(T_1 - T_2)^2}$$

$$\frac{\partial E}{\partial E_1} = \frac{(T_{ref} - T_1)}{(T_1 - T_2)} + 1$$

$$\frac{\partial E}{\partial E_2} = \frac{(T_1 - T_{ref})}{(T_1 - T_2)}$$

$$U = \sqrt{\left(\frac{\partial E}{\partial E_1} \times U_{E1}\right)^2 + \left(\frac{\partial E}{\partial E_2} \times U_{E2}\right)^2 + \left(\frac{\partial E}{\partial T_1} \times U_{T1}\right)^2 + \left(\frac{\partial E}{\partial T_2} \times U_{T2}\right)^2}$$

Example Calculations

Typical Values:

Measurement Device	Uncertainty	
Thermocouple	0.2 °F	95 % confidence
Watt-hour meter	1 %	95 % confidence

Point 1:

$T_1 = 5.888^\circ F$

$U_{T_1} = 0.2^\circ F$

$E_1 = 463.397 \dfrac{kW \bullet h}{year}$

$U_{E_1} = 4.63397 \dfrac{kW \bullet h}{year}$

Point 2:

$T_2 = 18.444^\circ F$

$U_{T_2} = 0.2^\circ F$

$E_2 = 339.633 \dfrac{kW \bullet h}{year}$

$U_{E_2} = 3.39633 \dfrac{kW \bullet h}{year}$

$$E = \frac{463.397 \frac{kW \bullet h}{year}\left(15.0^\circ F - 18.444^\circ F\right) - 339.633 \frac{kW \bullet h}{year}\left(15.0^\circ F - 5.888^\circ F\right)}{5.888^\circ F - 18.444^\circ F} = 373.574 \frac{kW \bullet h}{year}$$

$$\frac{\partial E}{\partial T_1} = \frac{\left(463.397 \frac{kW \bullet h}{year} - 339.633 \frac{kW \bullet h}{year}\right)\left(15.0^\circ F - 18.444^\circ F\right)}{\left(5.888^\circ F - 18.444^\circ F\right)^2} = -2.7037 \frac{kW \bullet h}{year^\circ F}$$

$$\frac{\partial E}{\partial T_2} = \frac{\left(463.397 \frac{kW \bullet h}{year} - 339.633 \frac{kW \bullet h}{year}\right)\left(15.0^\circ F - 5.888^\circ F\right)}{\left(5.888^\circ F - 18.444^\circ F\right)^2} = 7.1533 \frac{kW \bullet h}{year^\circ F}$$

$$\frac{\partial E}{\partial E_1} = \frac{\left(15.0^\circ F - 5.888^\circ F\right)}{\left(5.888^\circ F - 18.444^\circ F\right)} + 1 = 0.2743 \qquad \frac{\partial E}{\partial E_2} = \frac{\left(5.888^\circ F - 15.0^\circ F\right)}{\left(5.888^\circ F - 18.444^\circ F\right)} = 0.7257$$

$$U = \sqrt{\left(0.27 \times 4.63 \frac{kW \bullet h}{year}\right)^2 + \left(0.73 \times 3.40 \frac{kW \bullet h}{year}\right)^2 + \left(-2.70 \frac{kW \bullet h}{year^\circ F} \times 0.2^\circ F\right)^2 + \left(7.15 \frac{kW \bullet h}{year^\circ F} \times 0.2^\circ F\right)^2}$$

$U = 3.167 \dfrac{kW \bullet h}{year}$ 95 % confidence